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THE INFLUENCE OF SLOPE DAMAGE ON THE KINEMATICS OF LANDSLIDES

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EXTENDED ABSTRACT

La stabilità di versanti in roccia è strettamente correlata alle caratteristiche litologiche, strutturali e geomorfologiche dell'ammasso roccioso, che definiscono la dimensione, ubicazione, e meccanismo di rottura della potenziale instabilità. I fattori ambientali, quali precipitazioni e variazioni in temperatura, tipici dell'area di studio, possono anche contribuire al distacco di frane.

Tipicamente, la caratterizzazione del versante e dell'ammasso roccioso che lo costituisce, è basata sullo stato attuale, e può quindi fornire indicazioni su stabilità e caratteristiche di resistenza valide al momento del rilievo. Tuttavia, è oramai noto che la stabilità dei versanti non è un elemento immutabile nel tempo. Eventi ciclici, stagionali, o comunque ripetuti, quali ad esempio terremoti, variazioni del livello della tavola d'acqua, ed il continuo gelo e disgelo dell'acqua interstiziale in alta montagna, nonché processi che sono permanentemente attivi all'interno del versante, quali il creep, ne causano un progressivo danneggiamento, il quale induce a propria volta un decadimento delle caratteristiche meccaniche dell'ammasso roccioso e quindi della stabilità del versante stesso. Generalmente, il danneggiamento può apparire in forma di fratture sulla superficie o in profondità all'interno del versante, evidenze di taglio e scivolamento lungo superfici di discontinuità strutturale, e fratturazione fragile della roccia intatta. Tale progressivo danneggiamento può rendere il versante più suscettibile allo sviluppo di instabilità e frane nel corso di eventi, per esempio sismici, di entità minore ad eventi che in passato non hanno causato frane.

Nonostante il fenomeno del danneggiamento rappresenti un processo che può potenzialmente controllare e, in alcuni casi, causare lo sviluppo di frane, allo stato attuale non sono disponibili linee guida che definiscano metodi di mappatura sistematica, classificazione, e quantificazione del danneggiamento. In questo articolo, utilizziamo una metodologia recentemente introdotta che mira a distinguere il danneggiamento di versante in quattro tipi, sulla base degli effetti cinematici (in termini di meccanismo di rottura e distacco) prodotti sul versante. Il danneggiamento di tipo 1, che causa una riduzione della resistenza a taglio e tensione lungo le superfici di distacco di blocchi di frana, ad esempio attraverso la rottura di ponti di roccia o il taglio delle asperità, senza influenzare il meccanismo di rottura della frana. Il danneggiamento di tipo 2 causa la formazione di una nuova superficie di distacco, non disponibile precedentemente, che permette il distacco e il movimento della frana, definendone quindi il meccanismo di rottura. Il danneggiamento di tipo 3 induce una deformazione interna del corpo di frana, rappresentando una condizione necessaria al movimento della frana stessa. Un tipico esempio è rappresentato dal danneggiamento che si sviluppa nella zona di transizione all'interfaccia tra il blocco attivo e il blocco passivo, in una frana biplanare. Il danneggiamento di tipo 4 è costituito dall'insieme degli elementi, sia interni che superficiali, che si sviluppano in conseguenza della deformazione. Tale danneggiamento non influenza pertanto il cinematismo della frana, ma può influenzarne il comportamento post-distacco.

In questo articolo, applichiamo questa metodologia per analizzare gli effetti del danneggiamento di versante sul comportamento e resistenza a lungo termine di tre frane in roccia: le frane di Downie e Hope, in Canada, e la frana di San Leo, in Italia. Per ogni sito, viene fornita una panoramica delle caratteristiche litologiche, strutturali, e geomorfologiche. Vengono poi analizzate le caratteristiche del danneggiamento, sulla base delle quali vengono individuati gli effetti sul cinematismo della frana, e, in generale, sul comportamento a lungo termine del versante.

L'articolo si conclude con delle considerazioni sulla necessità di sviluppare approcci e metodologie integrate, attraverso l'uso di metodi di tipo ingegneristico, geofisico e geomorfologico, per definire un quadro completo dello stato di danneggiamento dei versanti, per quantificarne la stabilità e il comportamento nel lungo periodo, migliorando in ultima analisi la capacità di classificazione, gestione e mitigazione della pericolosità e del rischio da frana.

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ABSTRACT

The stability of large rock slopes is controlled by geological, structural, geomorphic, and environmental factors, which define the location, size, and failure mechanism of landslides. However, the stability of a slope can change with time, as a result of the formation and accumulation of slope damage, which weakens the rock mass forming the slope or the rupture surface of the incipient landslide. In this paper, we review three landslide sites, analysing the characteristics of the slope damage, and highlighting its effects on the kinematics of the slope and the evolution of the landslide. We note that, despite the importance of slope damage in controlling the timing and evolution of a slope failure, no frameworks or guidelines currently exist for performing a consistent and systematic analysis. We also emphasize that interdisciplinary approaches should be developed to assist in the quantification and characterization of rock slope damage.

Keywords: *landslide, slope damage, slope kinematics, Downie Slide, Hope Slide, San Leo landslide*

INTRODUCTION

The location, size, and failure mechanism of large landslides in rock is controlled by a broad range of factors. Depending on their orientation, spacing, and persistence, lithological features (such as bedding planes) and structural discontinuities at various scales (from cm-scale joints to slope-scale faults) can provide release surfaces along which volumes of rock mass can displace and detach from the slope (Stead & Wolter, 2015). The geomorphic configuration of the slope is also an important factor controlling rock slope instability. Steep slopes can cause discontinuities acting as basal surfaces to daylight, allowing the displacement of landslides. Deeply incised gullies can promote slope instability by reducing the frictional (i.e., shear) resistance along the side of the landslide or by limiting the support to the landslide volume, thus allowing displacement of the landslide towards the gully (Ganerød *et alii*, 2008; Brideau & Stead, 2012).

The lithological, geomorphic, and structural characteristics of a rock slope define its kinematic configuration, and control the failure mechanism and style of deformation of landslides in rock. However, unfavorable slope kinematics does not represent, per se, a sufficient condition for the detachment and displacement of a landslide. The long-term stability of rock slopes is controlled also by the accumulation of slope damage, which forms as a result of geological, geomorphological, and environmental processes, permanently weakening the rock mass and causing landslides to develop within previously stable slopes (Donati *et alii*, 2020; Stead & Eberhardt, 2013). As these processes are generally cyclical (e.g., seasonal or recurrent events) or continuously active, time is a critical factor for the development of slope damage and, thus, the occurrence of landslides. Ground-shaking due to earthquakes can cause intact rock fracturing and discontinuity dilation within the rock slope (Gischig *et alii*, 2015; Collins & Jibson, 2015), weakening the rock mass while enhancing the potential for seismic wave amplification in subsequent seismic events (Gischig *et alii*, 2016). Cyclical ground water table fluctuation can induce rock mass dilation and fracturing (Piller 2021; Preisig *et alii*, 2016). Thermal and cryogenic processes, such as freeze/thaw cycling and ice segregation can induce brittle rock fracturing and discontinuity propagation in alpine and high latitudes environments (Matsuoka, 2001; Hales & Roering, 2007). Continuously active processes such as rock mass creep (Chigira, 1992) and sub-critical crack growth (Kemeny, 2003) can also induce a progressive reduction in rock mass strength both within the landslide (or incipient landslide) body and along the release surface (or incipient release surface). The deformation of bi- and multi-planar landslides is also associated with the development of slope damage (rock mass dilation, intact rock fracturing, shearing of discontinuities within the prism-shaped transition zone between the active block (i.e., the upper part of the landslide, driving the displacement) and the passive block (i.e., forming the lower part, resisting the displacement) (Kvapil & Clews, 1979).

Despite its important role in controlling both the stability and evolution of rock slopes, slope damage is often considered a consequence of slope deformation, and its effects on slope evolution rarely addressed. The lack of framework or guidelines for its systematic characterization is arguably a reason for the limited consideration given to slope damage in the context of rock slope characterization. In this paper, we review three landslides, analyzing the various slope damage features that developed prior to and during failure, and their effects on the stability and evolution of the rock slope. We also preliminarily classify slope damage using an approach based on the impact on the slope kinematics introduced by Donati *et alii* (2023).

TYPES OF SLOPE DAMAGE

According to Donati *et alii* (2023), four types of slope damage features can be distinguished, as a function of the effect of slope kinematics.

Type 1 slope damage features occur along the well-defined boundaries of landslides, and can include the brittle failure in tension or in shear of in-plane or out-of-plane rock bridges, as well as shearing of asperities along existing discontinuities. In general, the development of type 1 slope damage features promotes the failure through a decrease of the shear and tensile strength available along the release surfaces. However, the kinematic failure mechanism (e.g., planar, wedge, toppling failure) does not change as a result of damage accumulation.

Type 2 slope damage features cause the formation of a new, fully persistent release surface within the rock slope, that causes the detachment of a previously non-removable landslide block, therefore affecting the kinematics of the rock slope. Brittle rock fracturing and discontinuity propagation causing the failure of a non-daylighting wedge (Havaej *et alii*, 2014a), a footwall failure (Havaej *et alii*, 2014b), or the formation of a hinge zone within a slope affected by flexural toppling (Adhikary *et alii*, 1997) are all examples of type 2 slope damage.

Type 3 slope damage forms within the body of the landslide and causes an internal deformation that constitutes a kinematic requirement for the displacement of the unstable volume. The rock mass dilation, fracturing, and shearing occurring within the transition zone of a bi-planar landslide is an example of type 3 slope damage.

Type 4 slope damage is constituted by internal or surface features that form after the detachment of the landslide, therefore representing an effect of the failure. Type 4 slope damage does not affect slope kinematics but can impact the behavior and mobility of the landslide body after the detachment. The fragmentation that occurs within the rock mass during the downslope displacement of a landslide is an example of type 4 slope damage.

In this paper, we also analyze slope damage features according to Stead & Eberhardt (2013), who introduced a distinction between internal and external (or surface) damage, depending on the location within the slope, and shear and tensile, as a function of the formation mechanism.

SLOPE DAMAGE ANALYSIS AT THREE LANDSLIDE SITES

In this section we review three landslides that differ significantly in terms of the rock type involved, failure mechanism, post-failure behavior, and geomorphic characteristics: the Downie Slide and the Hope Slide, in western Canada, and the San Leo landslide in northern Italy. For each site, a brief geological, geomorphic, and structural overview is provided, before summarizing the characteristic of slope damage features observed and discussing their effects on the landslide kinematics, evolution, and behavior.

The Downie Slide

The Downie Slide is an extremely slow landslide located on the western slope of the Revelstoke Reservoir, along the Columbia River Valley. The reservoir is impounded by a gravity dam built in the 1970s along the Columbia River, near the town of Revelstoke (British Columbia, Canada). The Downie Slide has a surface area of 9 km^2 and extends 2.4 km in the N-S direction and 3.2 km in the E-W direction (Fig. 1a). The toe of the slide is located at an elevation of 507 m a.s.l., about 65 m below the surface of the reservoir. The subvertical headscarp is 125 m high, and its maximum elevation is 1520 m a.s.l. (Piteau *et alii*, 1978). The volume of the landslide has been estimated at 1 billion m^3 (Donati *et alii*, 2021a).

The body of the landslide consists of an alternation of schists, marbles, and quartzites, which are part of the Monashee Metamorphic Complex and Proterozoic to Paleozoic in age (370 to 2,200 million years, Read & Brown, 1981). The major structural element in the area is the East-dipping Columbia River Fault, which controls and the location and orientation of the Columbia River Valley. This fault represents a structural decollement along which bedrock formations of the Selkirk allochthon (Proterozoic to Middle Mesozoic) displaced easterly and now form the eastern slope of this structurally controlled fluvial valley (Read & Brown, 1981).

Over fifty boreholes have been drilled and instrumented since 1973, largely in the lower part of the slope. Today, five borehole inclinometers and ten piezometers are actively used to monitor landslide displacement rates and ground water pressure. Borehole and inclinometer logs indicate the presence of two independent sliding surfaces at depths of about 250 and 120 m, referred to as “lower shear zone” (LSZ) and “upper shear zone” (USZ), respectively. The morphology of the LSZ, in particular, is characterized by a multi-planar morphology. An active-passive block configuration was noted, due to a decrease in the dip angle of the shear zone in the lower slope. Moreover, an E-W striking geological structure crosses and bisects the landslide (Donati *et alii*, 2021a). The rate of displacement is greater along the LSZ (up to 3.5 mm/yr) than along the USZ (up to 2 mm/yr). Present-day displacement rates are lower than those (up to 10 mm/yr) measured in borehole inclinometers prior to 1973. The construction of two drainage adits between 1973 and 1982, totaling 2,400 m in length, significantly decreased the ground water table elevation in the lower slope before the reservoir impoundment in 1983 (Imrie *et alii*, 1992).

Slope Damage At The Downie Slide

The morphology of the landslide ground surface is characterized by significant spatial variations. Donati *et alii* (2021a) used an airborne laser scanning (ALS) dataset to perform an engineering geomorphic characterization of the landslide surface and proposed subdivision into four “slope damage domains” based on the type, orientation, size, and distribution of surface slope damage features (Fig. 1b). The upper part of the slope constitutes the upper distributed damage domain (UD). It is characterized by a significantly rougher surface compared to the rest of the slide, and was formed through the progressive accumulation of blocks that detached during the retrogression of the headscarp (Donati *et alii*, 2021a; Kalenchuk *et alii*, 2013). The slope damage in this largely represented by open tension cracks separating blocks, or formed within blocks due to the dilation of the rock mass that constitutes the block. The central part of the slope is characterized by a relatively smooth surface, without prominent slope damage features. The absence of damage features in this area, referred to as the central undamaged domain (CD), is likely due to the planar geometry characterizing both the USZ and the LSZ in this area. The lower slope is divided into

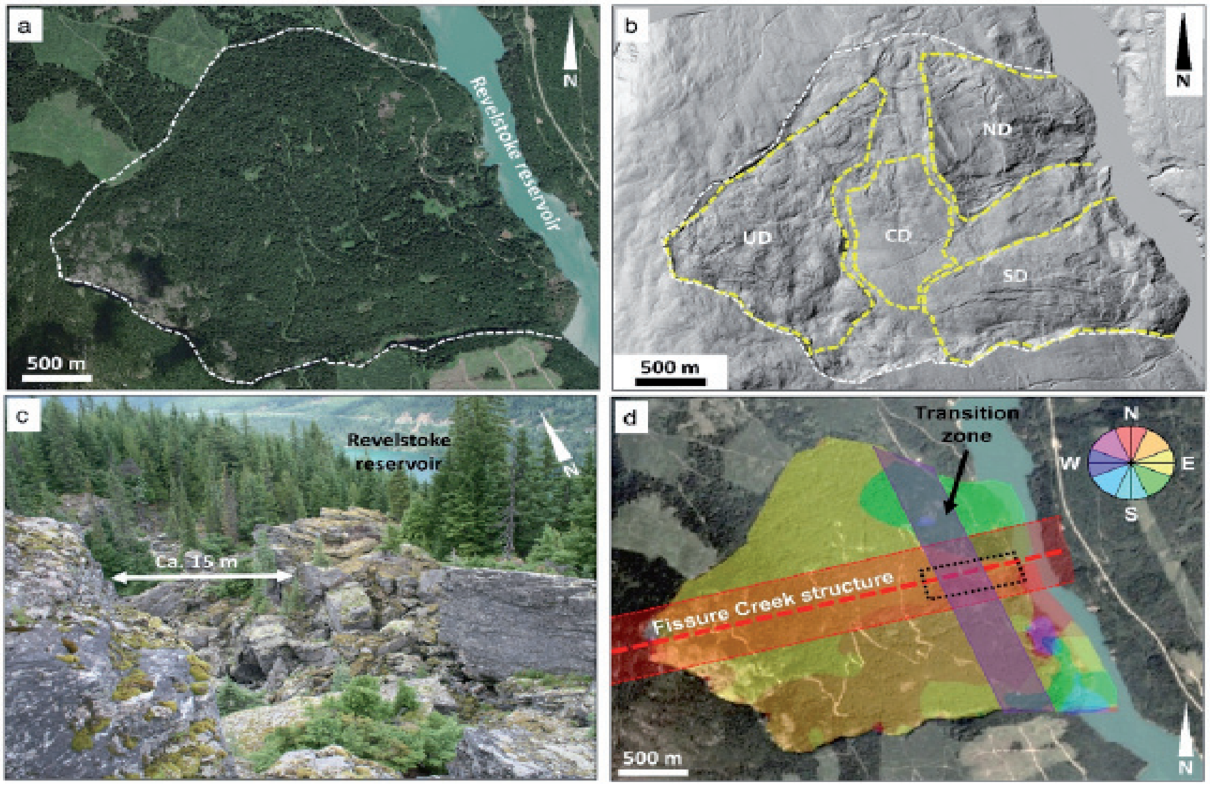

Fig. 1 - Summary of the Downie Slide analysis. a: satellite image (from Google Earth) of the Downie Slide. The white, dashed line marks the boundaries of the landslide area. b: subdivision of the landslide area in slope damage domains. UD: upper distributed damage domain, CD: central undamaged domain, ND: northern slope damage domain, SD: southern slope damage domain. c: interpreted correlation between LSZ orientation (coloured based on dip direction), structural damage zone of the Fissure Creek structure, and transition zone between the active block (central and upper slope) and passive block (lower slope). The most active area in the landslide is outlined by the black, dotted line, and occurs at the intersection between the Fissure Creek structural damage zone and the transition zone. d: example of a slope damage feature (a 15 m wide open tension crack) observed in the ND domain

two damage domains, which are characterized by a significant variation in the orientation of slope damage lineaments. The southern slope damage domain (SD) is characterized by E-W open fissures that extend for up to 500 m, parallel with the southern boundary of the landslide. The ALS datasets shows that such fissures are characterized by a stepped morphology, suggesting that their origin is due to the opening and connection of smaller scale rock mass discontinuities (e.g., joints).

The northern damage domain (ND) is characterized by prominent tensile cracks extending in a N-S direction with an aperture in some cases of over 10-15 m, particularly in the area referred to as "north knob" (Fig. 1c).

Slope damage features observed across UD, SD, and ND spatially correlate with parts of the LSZ that display an upward concavity (based on shear zone reconstruction in (Donati *et alii*, 2021a). Therefore, most of the described surface slope damage features can be interpreted as resulting from the displacement of the landslide over an irregular sliding surface, and thus can be ascribed to type 4 slope damage.

A significant amount of internal damage was noted along the shear zones, particularly the LSZ, where the 300 m displacement of the landslide over the 7000 years of landslide activity resulted in the formation of a damage zone locally up to 60 m thick, particularly in the lower slope, at the base of the passive block. There, intense shearing and an overall decrease of rock mass quality was observed in rock cores. Such a significant thickness of the damaged zone may be the result of local undulations of the sliding surface that became sheared as the displacement progressed, or the presence of multiple sliding surface that had been active in the past (Donati *et alii*, 2021a). In the interpretation of a displacement-driven shearing of large-scale asperities and undulations along the sliding surface, the damage zone that surrounds the shear zones, can be considered a type 1 slope damage feature.

The southern and rear boundaries of the landslide formed through opening and shearing along structural discontinuities connected to form stepped surfaces. Shearing or tensile failure of rock bridges along these surfaces can be considered as type 1 slope damage.

The internal slope damage that characterizes the transition zone of the landslide represents a kinematic requirement for the displacement of the Downie Slide and can therefore be ascribed to type 3 slope damage. The combination of a) shear, internal slope damage along the LSZ, b) internal slope damage within the transition zone caused by multi-planar sliding surface morphology, and c) the structural damage zone affecting the rock mass along the E-W trending geological structure results in a superposition of damage and damage types (Fig. 1d), resulting in particularly high activity and rock fall frequency observed in the central part of the lower slope (Donati *et alii*, 2021a).

The 1965 Hope Slide

The Hope Slide is a 47 million m^3 rock avalanche that detached, in two stages, on January 9th, 1965, from the western slope of the Johnson Ridge, 10 km south-east of the town of Hope (British Columbia, Canada). The first event occurred in the early morning, around 4:00 am, while the second event occurred at 7:15 am. The landslide completely obliterated a section of the Hope-Princeton Highway and filled Outram Lake located at the bottom of the slope. The debris travelled along the Niculum Valley for about 2 km, and raised the valley floor by 60 m, compared to its pre-failure elevation. Four people were killed during the second event. Two small earthquakes (with MW between 3.2 and 3.1) were recorded in the area at the time of the events (Mathews & McTaggart, 1969). While initially suggested to be the cause of the landslide, later studies showed that they represented the two landslide events themselves (Weichert *et alii*, 1994).

The landslide extended vertically between elevations of 870 m and 1800 m a.s.l. and measured approximately 800 m across slope. The bedrock comprises formations of the Hozameen Group: Greenstone, a weakly metamorphosed rock of volcanic origin, and Felsite, an aphanitic volcanic rock that occurs, at this site, as a white and a pink variety forming dikes and sills within the massive Greenstone.

The slope from which the Hope Slide detached experienced an earlier landslide approximately 9,700 years b.p., at the end of the Fraser glaciation, similar in size to the 1965 event (Mathews & McTaggart, 1969). The ancient landslide deposit could also be observed in historical air photographs, which display a blocky deposit across the valley floor that hosted, until 1965, the Outram Lake (Donati *et alii*, 2021b).

The behaviour and evolution of the 1965 Hope Slide was controlled by a combination of lithological, structural, and geomorphic factors. The landslide displaced along discontinuities sub-parallel to the slope orientation (Fig. 2a). Slope-scale geological structures divided the landslide in four blocks that moved independently during the multi-stage event (blocks 2-4 during the first failure, block 5 during the second failure, Donati *et alii*, 2021b). The pre-historic landslide, which detached from the lower part of the slope, was also a structurally-controlled failure (block 1 in fig. 2a), and formed a "keyblock" in the slope, promoting the subsequent failure in 1965.

Slope Damage At The Hope Slide

The long-term stability and geomorphic evolution of the slope has been strongly controlled by the development and accumulation of slope damage.

The detachment of the pre-historic landslide was promoted by the glacier action and evolution. During the Fraser glaciation, the erosive action of the glacial ice promoted a progressive steepening of the slope. Such process promoted a stress redistribution and the initiation of a slow slope deformation, as glacier ice, due to rheology and mechanical characteristics, is not capable of fully supporting and prevent deformation of valley slopes (Gramiger

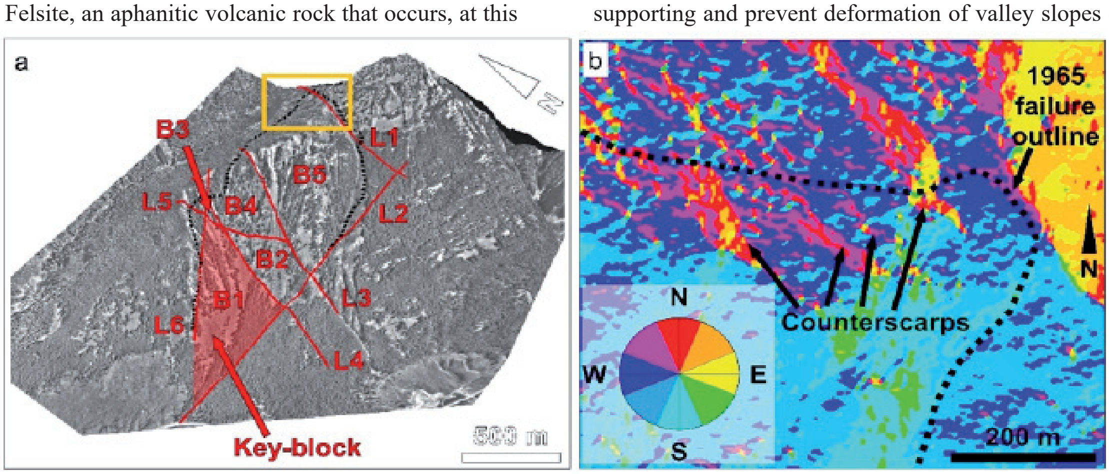

Fig. 2 - Geological structures and surface slope damage at the Hope Slide. a: pre-failure 3D model of the Hope Slide (derived from Structure-from-Motion analysis) showing the structural lineaments within the slope and the blocks they define. The block B1, highlighted in red, represent a keyblock for the slope, and failed in the prehistoric landslide. The 1965 event was formed by blocks B2, B3, B4 (failed in the first event of January 9th, 1965) and B5 (failed in the second event). The orange box shows the area depicted in b. b: aspect map of the pre-failure model, showing the counter-scarps that developed in the upper slope, near the crest (dotted, black line)

et alii, 2017; McColl *et alii*, 2010). As the glacier retreated at the end of the glaciation, the slope became kinematically free, and the pre-historic failure occurred. In turn, the pre-historic failure enhanced the kinematic freedom in the upper part of the slope, causing the initiation of a very slow deformation process (Evans & Couture, 2002). Fracture propagation (possibly through subcritical crack growth) along the incipient basal surface, which ultimately led to the detachment of the 1965 landslide (Donati *et alii*, 2021b), can be considered evidence of type 1 slope damage. The factor of safety, controlled by shear strength (due to in-plane rock bridges) and tensile strength (due to out-of-plane rock bridges) along the incipient rupture surface decreased as slope damage progressed. However, the landslide kinematics (i.e., the failure mechanism) was not affected by slope damage accumulation.

In the upper part of the slope, in proximity of the incipient headscarp, a series of counterscarps (also noted by Eisbacher & Clague, 1984) developed during the progressive slope damage accumulation at the base of the landslide (Fig. 2b). The NW-SE strike of such features was normal to the maximum slope steepness, and thus had limited or no control on the development of the headscarp, which in fact occurred through tensile failure and opening along a SW-NE striking, sub-vertical discontinuity set (type 1 slope damage). We conclude that the counterscarps represented the surface expression of the internal deformation of the landslide body, but were not kinematically required for the landslide development, and can therefore be ascribed to type 4 slope damage.

The 2014 San Leo Landslide

The town of San Leo is located in the northern Apennines, within the Val Marecchia district. It is located on top of a rocky plateau constituted by sandstones of the Monte Fumaiolo formation (middle Miocene) and limestone-calcarenite alternations of the San Marino formation (early to middle Miocene). The plateau overlies soft clay shales of the Argille Varicolori formation.

The landslide detached on February 27th, 2014 and involved about 300,000 m^3 of the Monte Fumaiolo sandstone rock mass. The landslide occurred as a toppling failure, due to a progressive, long term lateral spreading deformation that affects the San Leo plateau, as well as similar plateaux across the Val Marecchia (Borgatti *et alii*, 2015). The 2014 landslide, in particular, was promoted by the progressive erosion of the clay shale material that resulted in the undermining of the sector of the plateau involved in the failure (Spreafico *et alii*, 2017). The landslide deposit induced a peak in ground water pressure within the clay shale, which resulted in the undrained failure and initiation of an earthflow that remains presently active. No injuries or fatalities were registered, however, various buildings in San Leo were evacuated due to safety concern, in view of the proximity to the landslide crown.

After the failure, a sub-vertical, highly weathered discontinuity plane (referred to as SL3.1 in technical reports and published literature) became visible in the upper part of the landslide scar (Fig. 3a). In view of its relatively high persistence (with respect to the size of the failure) and position, it has been considered an important controlling factor for the landslide stability and size (Borgatti *et alii*, 2015). Beside SL3.1, the morphology of the landslide scar does not display a significant correlation with any of the discontinuity sets identified within the rock mass. However, the trace of four faults can be recognized, that intersect sub-perpendicularly the scar, which separated the landslide body in blocks that detached in rapid succession (Donati *et alii*, 2019).

In the aftermath of the failure, a series of borehole inclinometers, piezometers, extensometers (including downhole), and seismometers was installed across the area behind the crest, to monitor the potential evolution or retrogression of the instability. However, no significant trends of deformation could be identified (Donati *et alii*, 2021c).

Slope Damage At The San Leo Landslide Site

After the 2014 landslide, various remote sensing surveys were undertaken, including digital photogrammetry and terrestrial laser scanning, to characterize the rock mass (e.g., through virtual discontinuity mapping) and identify evidence of slope damage across the rear release surface. Rough, fresh surfaces were noted frequently across the landslide scar (Fig. 3b,c), and were interpreted as the result of brittle fracturing that occurred at the rear of the landslide volume (Donati *et alii*, 2021c; Spreafico *et alii*, 2017).

Numerical modelling was performed to investigate the role of SL3.1, intact rock fracturing, as well as plateau undermining (due to clay shale erosion) on the long-term evolution of the slope. 2D and 3D numerical modelling was performed using the FDEM (finite-discrete element method) code Elfen (Rockfield Software Ltd, 2017) and the lattice-spring code Slope Model (Itasca CG, 2020), respectively, both of which are capable of simulating brittle fracturing of intact rock. Simulations showed that the progressive erosion of the clay shale deposit induced a stress concentration within the rock mass near the tip of SL3.1, as well as at the edge of the eroded clay shale volume. As erosion and undermining progressed, stress concentration increased in magnitude, until the propagation of SL3.1 was simulated. The coalescence with pre-existing discontinuities along the incipient rupture surface ultimately caused the separation of the landslide body from the plateau (Fig. 3d).

Numerical modelling indicated that brittle fracture propagation played a critical role in the failure, and in fact controlled its kinematic release mechanisms, which initiated and evolved as an oblique toppling failure. In this instance, slope damage caused the formation of a previously unavailable rupture surface that allowed the detachment of the landslide. Therefore, brittle damage prior to the detachment of the San Leo landslide is an example of type 3 slope damage.

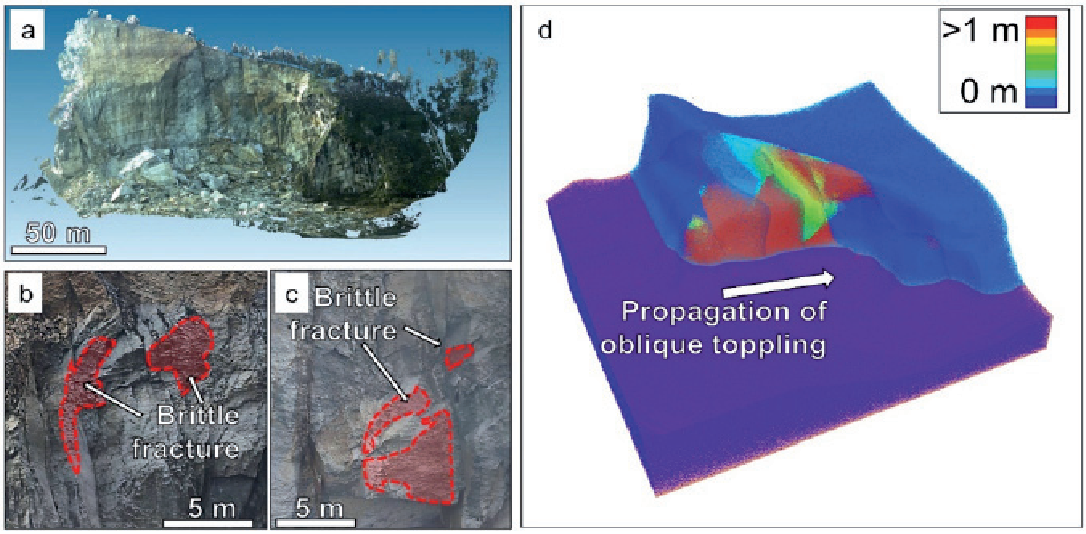

Fig. 3 - Overview of the Slope damage analysis at the San Leo landslide site. a: 3D model of the landslide scar from Structure-from-Motion. b,c: examples of brittle damage features observed across the scar, characterized by rough surfaces connecting structural discontinuities. d: Numerical modelling of the San Leo landslide. The progressive, brittle propagation of discontinuities caused the initiation of an oblique toppling failure that progressed from East to West (view of the model from North)

DISCUSSION AND CONCLUSIONS

The analysis of rock slopes with varied lithological, structural, and geomorphic features indicates that the progressive development of slope damage can significantly affect the long-term stability and evolution. As slope damage accumulates, the overall strength of the rock mass and/or the (incipient) rupture surface decreases, together with the factor of safety of the slope. As a result, rock slopes that appear to have remained stable for a long time period, suddenly become unstable and landslides occur. Surface expressions of slope damage, such as open cracks, counterscarps, and other lineaments, often represent an indication of an active or cyclical slope deformation (or a deformation that had been active in the past) and need to be adequately investigated in order to identify the potential impacts on future stability and slope kinematics.

The lack of guidelines or a framework for the systematic, quantitative description and classification of slope damage, however, makes it challenging to correlate external slope damage features observed at the surface and internal slope damage present at depth with the potential effects on stability. The approach described in Donati *et alii* (2023), briefly outlined in this paper and applied to a set of well-known landslides, represents a first step towards the development of a damage classification framework, in which the effects of damage on slope kinematics are considered. In future research, a critical aspect that needs to be undertaken is the review and harmonization of the approaches that are available for damage analysis, in order to enhance communication and consistency (e.g., in terms of methods and terminology) across the involved disciplines, from engineering to geomorphology.

Presently, slope characterization (and slope damage) analyses focus on the present stability conditions. It is understood, however, that slope damage accumulation cause changes in stability conditions, progressively driving the slope to more unstable conditions, ultimately causing a landslide. Nevertheless, inferring "how close" a slope is to the failure, estimating what is the amount of slope damage that can develop before failure, and what is the type and magnitude of process (e.g., earthquakes, erosion, and so on) is extremely challenging due our present level of technology and scientific knowledge in addition to the high level of uncertainty associated with available geological data. Multi-disciplinary approaches, that involve geophysics, geomorphology, hydrogeology and engineering geology fields need to be developed to address this challenge. The ultimate objective being to obtain an improved knowledge of the level of hazard associated with the investigated slope, increasing our ability to assess and manage landslide risk, and thereby enhancing the safety of communities and infrastructures.

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